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Investigations of thermal aberrations in Nd:YAG laser end-pumped by 10 W fiber coupled diode bar

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Thermally induced aberrations in Nd:YAG laser pumped by 10 W fiber coupled bar are investigated theoretically and experimentally in this paper. As a result of theoretical analysis based on numerical solution of ray equation, it has been found that severe wavefront distortions are generated outside the pump volume, whereas for beam confined inside pump volume the aberration effects are negligible. Interferometric inspection of wavefront distortion and caustics shape measurements confirm qualitatively the theoretical predictions.

1. Introduction

Diode end-pumped lasers with pumping volume comparable to fundamental mode generate, as a rule, near diffraction limited beam [1]–[3]. The Gaussian shape of intensity distribution is observed in every section. As a rule, with increase of pump power, Rayleigh range decreases and divergence increases due to thermal lensing, whereas the beam quality does not change (see, *e.g.* [4], [5]).

However, for higher pump density the degradation of beam quality was observed in several diode end-pumped lasers [5]–[8]. As a rule, multimode beam with strong outer rings is generated. FRAUCHIGER *et al.* showed in [6] that higher mode oscillation occurs in near confocal cavities for high pump level. TIDWELL *et al.* showed that for high thermal load it is possible to compensate thermal distortions by aspherical mirror [7]. BYER and KEIERSTEAD [8] analyzed similar effects in Nd:YVO_4 and Nd:YLF lasers and showed that it is possible to compensate it despite high wavelength aberration.

In our previous work [5], we observed that for high pump density thermal distortion of active medium causes atypical shape of caustics. Gaussian-like as well as Bessel-like and annular intensity distribution patterns were observed in the caustics after passing through long focal length, aberration-free lens. The aim of this paper was to analyze these effects theoretically and to verify them in experiments for Nd:YAG laser pumped by 10-W fiber coupled bar. In Section 2, the wavefront distortion based on the ray equation calculation is theoretically analysed. In the next sections, the results of experimental investigation of thermal distortions in non-lasing conditions as well as caustics shape are presented.

2. Calculation of thermal aberrations

To calculate refractive power of thermal lens, temperature distribution in the active medium should be determined. Assuming homogeneous heat source distribution with averaged radius R_p, the temperature distribution in active medium can be determined in analytical form (see, *e.g.*, [6], [7], [9]). Knowing thermal dispersion dn/dT, thermal expansion coefficient α_T and photoelastic coefficient $C_{r,\varphi}$ of active medium, we can calculate the refractive index changes (see, *e.g.*, [7]) and the resulting thermally aberrated wavefront, as well as thermal lensing refractive power. In the first order approximation, neglecting non-parabolic components of aberrated wavefront, the refractive power of thermal lens P_T is proportional to pump power P_P as follows:

$$P_T = \beta P_P \tag{1}$$

where β denotes the thermal sensitivity factor given by

$$\beta = \frac{\eta_h}{K_c A_p} \varkappa [1 - \exp(-\alpha l_c]^{-1}, \tag{2}$$

η_h – fractional thermal loading factor (see, *e.g.*, [16]), K_c – thermal conductivity of the active medium, A_p – averaged pump area, α – absorption coefficient, l_c – length of the crystal. Factor $\varkappa$ consists of thermal dispersion, axial expansion and stress induced changes of refractive index as follows [7]:

$$\varkappa = \frac{dn}{dT} + (n_p - 1)(1 + \nu)\alpha_T + n_p^3 \alpha_T C_{r,\varphi} \tag{3}$$

where n_p denotes the refractive index of active medium without heat load and ν denotes Poisson ratio. To calculate β we must determine A_p for a given pump scheme and know η_h. As it was measured in [10], η_h is approximately 0.35–0.4 for Nd:YAG crystal.

However, as was shown by BECKMANN in [11], even inside pump region the spherical aberration cannot be neglected. Though we decided to calculate the optical path differences (OPD) exactly as a solution of ray equation assuming the following temperature distribution model (see, *e.g.*, [7], [11]):

$$T_{inc}(r,z) = T(r,z) - T_0 = \Delta T_0(z) \begin{cases} -2\ln(R_p/R_0) + 1 - (r/R_p)^2; & r \leqslant R_p \\ -2\ln(r/R_0); & r > R_p \end{cases} \tag{4}$$

where $T_{inc}(r,z)$ – temperature difference in point (r,z) with respect to edge temperature T_0, R_p – averaged radius of pump volume, R_0 – radius of the rod, and $\Delta T_0(z)$ denotes temperature difference between the center and the edge of the rod given by

$$\Delta T_0(z) = \frac{\eta_h P_p \exp(-\alpha z)}{4\pi K_c l_c}. \tag{5}$$

Let us formulate the ray equation problem for the gradient index medium (see, *e.g.*, [12])

$$\frac{d^2r}{dz^2} = \frac{1}{C_i^2}[n_p + \varkappa T_{inc}(r,z)]\varkappa \frac{dT_{inc}(r,z)}{dr} \tag{6}$$

with initial conditions given for $z = 0$

$$r(0) = r_i, \quad \frac{dr}{dz} = 0, \quad C_i = n_p + \varkappa T_{inc}(r_i, 0). \tag{7}$$

The type of solution of Eq. (6) depends on sign and magnitude of factor $\varkappa$, and range of r_i. For $r_i < R_p$ and low absorption we have classical analytical solution which leads to explicit analytical formulae on refractive power ((1), (2)). However, also in this range of r_i spherical aberration occurs and the beam has a weak wavefront distortion [11]. Such solution assuming constant temperature distribution along z axis can be obtained using, *e.g.*, OPDESIGN program worked out by Beckmann.

A program that solves this problem using standard Runge–Kutta procedure was worked out. The points r_i were fixed in nodes of Chebyshev polynomials. The parallel ray beam after passing through a thermal GRIN medium is analyzed, OPD is calculated, the aberration polynomial coefficients are derived, *etc.* We assumed that factor $\varkappa$ is dominated by thermal dispersion and equal to dn/dT. To compare numerical results with analytical solution the average focal length of ray bundle exiting from a GRIN medium was calculated and compared with results derived from formulae (1), (2), (see Fig. 1).

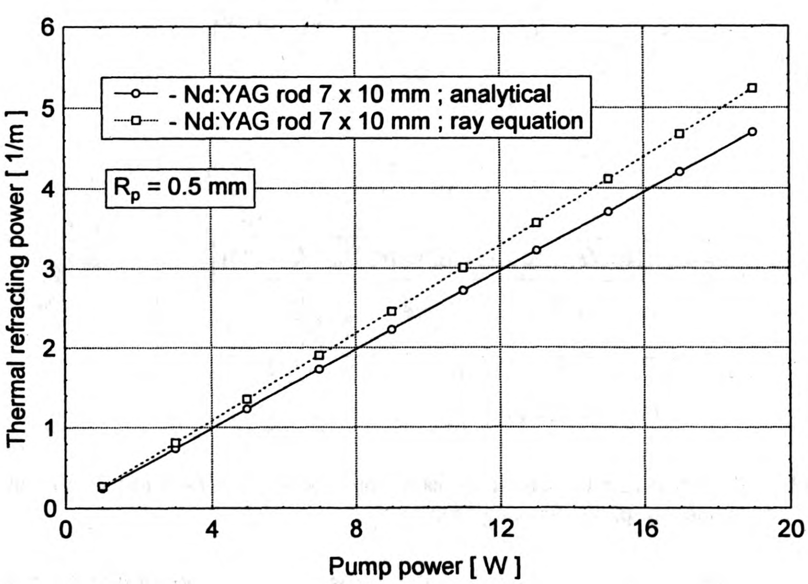

Fig. 1. Thermal refractive power versus pump power for Nd:YAG laser

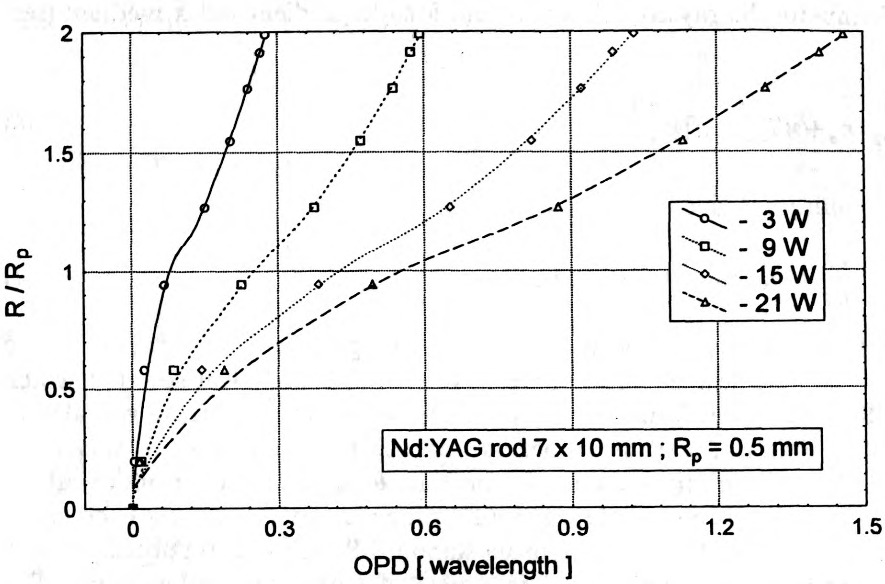

Fig. 2. OPD versus radius of incident rays for several values of pump power; Nd:YAG rod 7×10 mm, pump radius 0.5 mm, with parabolic component

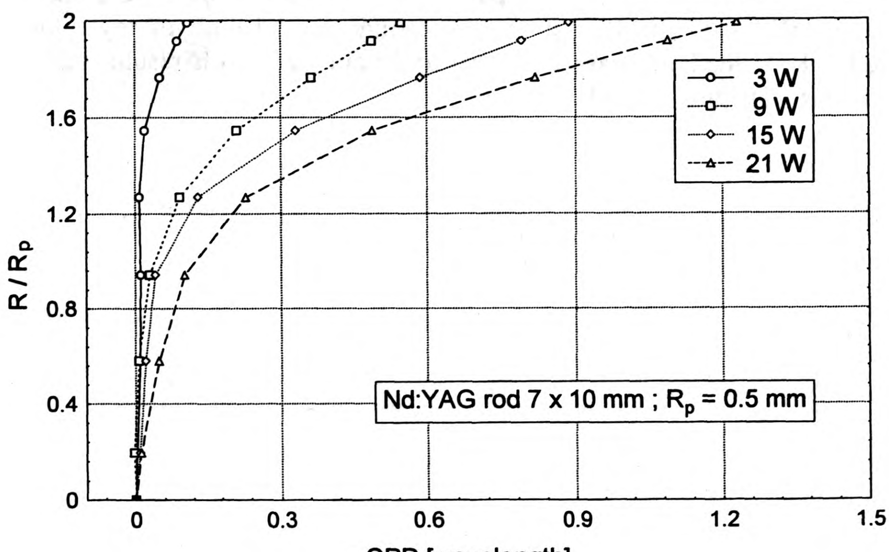

Fig. 3. OPD versus radius of incident rays for several values of pump power; Nd:YAG rod 7×10 mm, pump radius 0.5 mm; after removing parabolic component

More interesting is the case when $r_i > R_p$ and the absorption dependence on z is not neglected. In this case, we can observe very low OPD inside pump diameter whereas outside of it the severe conical-like aberration was obtained as a rule.

Such effect can be especially strong when we have very tight pump beam, with diameter much less than the fundamental mode of the cavity.

The results of OPD calculation with and without parabolic component are shown in Figs. 2 and 3. We suppose that conical-like aberration observed outside pump diameter $2R_p$ causes atypical intensity distribution patterns for higher pump level.

3. Interferometric wavefront inspection

There were performed interferometric investigations of wavefront distortions in non-lasing conditions. The interference patterns created between the entrance and outer facets of crystal by probing He-Ne beam were observed. After passing through relay optics [13], consisting of two aberration free objectives with focal length ratio 1.5, the pump radiation is focused on active medium, with averaged pump dia-

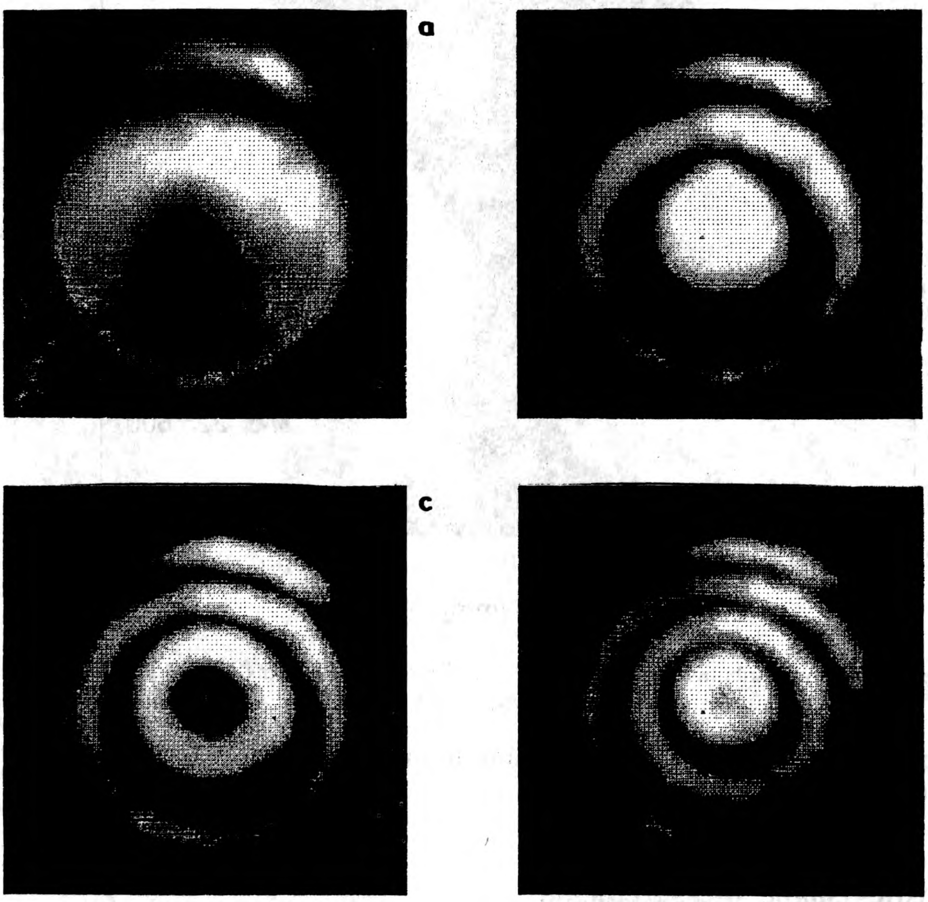

Fig. 4. Interferograms of thermally induced wavefront aberration of Nd:YAG rod 7×10 mm for several values of pump power: a – 2.7 W, b – 5.2 W, c – 7.5 W, d – 10.2 W

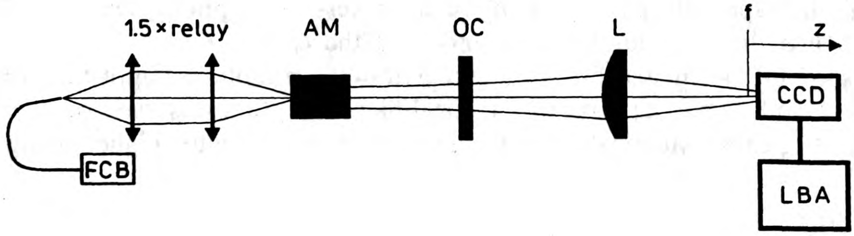

Fig. 5. Scheme of experimental setup: FCB — fiber coupled diode bar SDL3450-P5, AM — active medium (T-GRIN lens), OC — output coupler, L — lens, CCD — CCD camera Pulnix TM-745, LBA — laser beam analyser

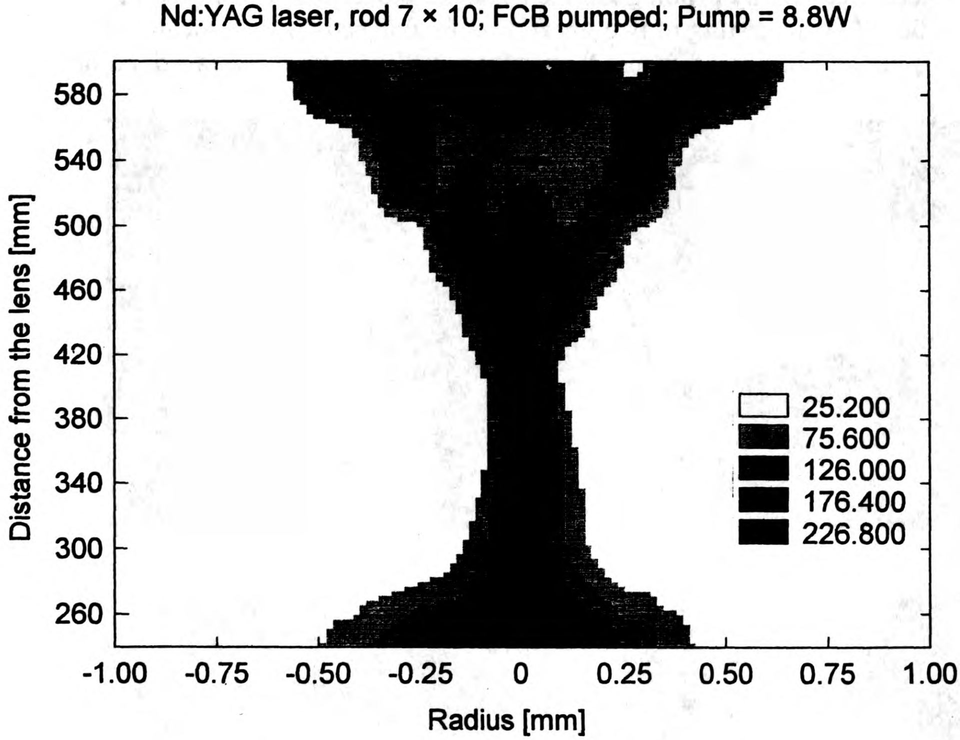

Fig. 6. Beam intensity distribution as a function of the distance from the lens of focal length 300 mm; Nd:YAG laser with 7×10 mm rod at 8.8 W pump power

meter of about 1 mm. The interferograms recorded for such a pump beam for Nd:YAG rod are shown in Fig. 4a-d.

4. Caustics shape measurements

An investigation of caustics shape and beam parameters in a set up shown in Fig. 5 was performed. To determine the waist location, radius and divergence in the

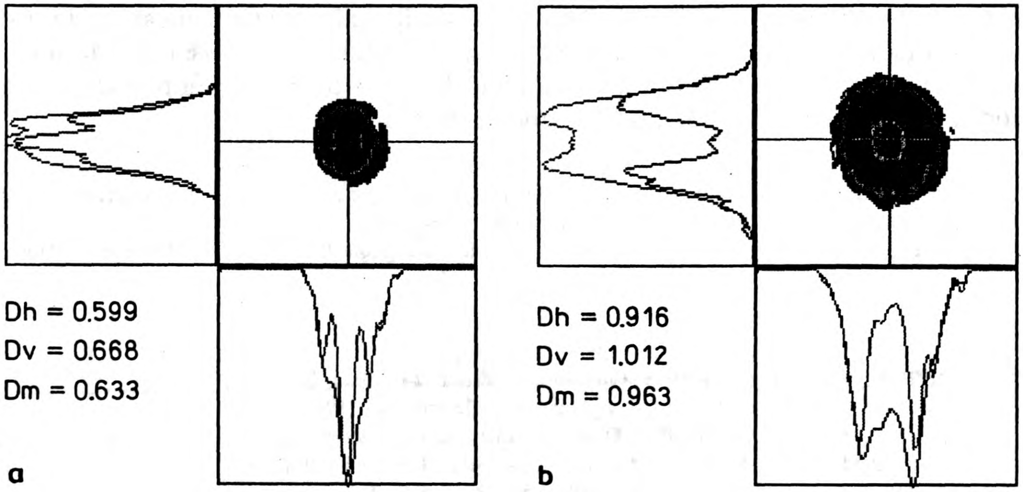

Fig. 7. Beam intensity distribution for the Nd:YAG laser: **a** — Bessel-like shape at a distance of 480 mm from the lens, **b** — annular-like shape at a distance of 520 mm from the lens

image space of the lens, a series of intensity distribution patterns for several distances from the lens were recorded and analysed (see, *e.g.*, [14]). The multimode beam, with Gaussian-like intensity distribution, was observed up to 6 W of incident pump power. Thus, in these cases the standard procedure of beam parameter definition could be applied.

For higher pump powers, the beam diameter in this case is not a smooth parabolic function of distance (see Fig. 6) and it is not possible to define the beam quality using the above method. The caustics is elongated compared to Gaussian beam and asymmetric with respect to waist plane. Atypical intensity distribution (see Fig. 7**a**,**b**) outside the waist can be caused, as we suppose, by conical-like wave aberration generated in this case. Additional effect which can play the same role is the gain guiding (see [15], [16]). As was shown by LONGHI and LAPORTA in [16], in the case of high gain gradients the Bessel-like or annular-like distribution can be observed.

5. Conclusions

The influence of thermal lensing and thermal aberration on beam parameters of diode end-pumped lasers was investigated theoretically and verified in experiments. Satisfactory agreement between analytical, numerical and experimental results of thermal lensing investigation was achieved. It was found that for the majority of cases the Gaussian-like intensity distribution occurs and a standard procedure of beam quality measurements can be applied. However, a significant deviation from this rule was observed for high pump density. The Bessel-like as well as annular intensity distribution patterns were recorded indicating the role of higher order aberrations in forming such beams. This effect was investigated theoretically in terms of ray equation and verified for two pump schemes. It should be taken into account especially in such lasers with high pumping density where the pump diameter is comparable to or less than that of fundamental mode.

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